Technical Note: Novel method for water vapor monitoring using wireless communication networks measurements

N. David, P. Alpert, H. Messer

Atmos. Chem. Phys. Discuss., 8, 11673–11684, 2008
www.atmos-chem-phys-discuss.net/8/11673/2008/

Atmospheric Chemistry and Physics Discussions

Technical Note: Novel method for water vapor monitoring using wireless communication networks measurements

N. David[1], **P. Alpert**[1], **and H. Messer**[2]

[1]The Department of Geophysics and Planetary Sciences, Tel-Aviv University, Tel-Aviv, Israel
[2]The School of Electrical Engineering, Tel-Aviv University, Tel-Aviv, Israel

Received: 22 April 2008 – Accepted: 14 May 2008 – Published: 12 June 2008

Correspondence to: N. David (noamda@post.tau.ac.il)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

We propose a new technique that overcomes the obstacles of the existing methods for monitoring near-surface water vapor, by estimating humidity from data collected through existing wireless communication networks.

Weather conditions and atmospheric phenomena affect the electromagnetic channel, causing attenuations to the radio signals. Thus, wireless communication networks are in effect built-in environmental monitoring facilities. The wireless microwave links, used in these networks, are widely deployed by cellular providers for backhaul communication between base stations, a few tens of meters above ground level. As a result, the proposed method can provide moisture observations at high temporal and spatial resolution. Further, the implementation cost is minimal, since the data used are already collected and saved by the cellular operators. In addition – many of these links are installed in areas where access is difficult such as orographic terrain and complex topography. As such, our method enables measurements in places that have been hard to measure in the past, or have never been measured before.

We present results from real-data measurements taken from two microwave links used in a backhaul cellular network that show excellent correlation to surface station humidity measurements. The measurements were taken daily in two sites, one in northern Israel (28 measurements), the other in central Israel (29 measurements).The correlation of the microwave link measurements to those of the humidity gauges were 0.9 and 0.82 for the north and central sites, respectively. The RMSE were 20.8% and 33.1% for the northern and central site measurements, respectively.

1 Introduction

Atmospheric humidity strongly affects the economy of nature and consequently has a cardinal part in a variety of environmental processes (e.g. Allan et al., 1999) in many fields. As the most influential of greenhouse gases, it absorbs long-wave terrestrial radiation. The water vapor cycle of evaporation and recondensation is a major energy redistributing mechanism transferring heat energy from the Earth's surface to the atmosphere. Meteorological decision-support for weather forecasting is based on atmospheric model results (e.g. Shay-El and Alpert, 1991), the accuracy of which is determined by the quality of its initial conditions or forcing data. Hence, humidity, in particular, is a crucial variable for the initialization of atmospheric models. One of the central conclusions of the Mesoscale Alpine Programme (MAP), aimed at improving prediction of the regional weather and particularly rainfall and flooding, was that accurate moisture fields for initialization are essential (Ducrocq et al., 2002).

Current methods for obtaining humidity measurements include predominantly, surface stations, radiosondes and satellite systems. Common humidity instruments, found in surface stations, suffer from low spatial resolution since they provide only very local point observations. Moisture, in particular, is a field having unusually high variability in the mesoscale as demonstrated, for instance, by structure functions (Lilly and Gal-Chen, 1983). Furthermore, over heterogeneous terrain and complex topography, the spread of gauges is even more restricted due to often poor accessibility and positioning difficulties. Satellites, although cover large areas, are frequently not accurate enough at surface levels while it is the near-surface moisture level that is, in many cases, the crucial variable for convection. Radiosondes, which are typically launched only 2–4 times a day, also provide very limited information. Additionally, these monitoring methods are costly for implementation, deployment and maintenance.

For model initialization, a point moisture measurement close to the surface (about 2 m, as in a standard meteorological station) is not satisfactory due to local surface perturbations. For meteorological modeling purposes, an area average representing the near-surface moisture at an altitude of a few tens of meters, over a box with the scale of the model's grid, is required. This type of data cannot, with use of current measuring tools, be effectively collected. The method we present provides a unique way of obtaining it.

As weather conditions and atmospheric phenomena cause impairments on radio links, wireless communication networks provide built-in environmental monitoring tools, as was recently demonstrated for rainfall (Messer et al., 2006; Messer, 2007; Leijnse et al., 2007) and areal evaporation (Leijnse et al., 2007) observations. In this paper we introduce a new technique to measure atmospheric humidity using data collected by wireless systems. Wireless communication, and in particular cellular networks, are widely distributed, operating in real time with minimum supervision, and therefore can be considered as continuous, high resolution humidity observation apparatus.

Environmental monitoring using data from wireless communication networks offers a completely new approach to quantifying ground level humidity. Since cellular networks already exist over large regions of the land, including complex topography such as steep slopes and since the method only requires standard data (saved by the communication system anyway), the costs are minimal.

Of the various wireless communication systems, we focus on the microwave point-to-point links which are used for backhaul communication in cellular networks, as they seem to have the most suitable properties for our purposes: they are static, line-of-sight links, built close to the ground, and operate in a frequency range of tens of GHz.

In this research, the wireless system used for humidity observations has a magnitude resolution of 0.1 dB per link. The length of an average microwave link is on the order of a few km and tends to be shorter in urban areas and longer in rural regions. In typical conditions of 1013 hPa pressure, 15°C temperature and water vapor density of 7.5 g/m^3, the attenuation caused to a microwave beam interacting with the water vapor molecules at a frequency of ~22 GHz is roughly around 0.2 dB/km (Rec. ITU-R P.676-6, 2005). Therefore, perturbations caused by humidity can be detected.

2 Theory and methods

At frequencies of tens of GHz, the main absorbing gases in the lower atmosphere are oxygen and water vapor. While oxygen has an absorption band around 60 GHz, water vapor has a typical resonance line at 22.235 GHz. Although other atmospheric molecules have spectral lines in this frequency region, their expected strength is too small to affect propagation significantly (Raghavan, 2003; Meeks, 1976).

As a consequence, an incident microwave signal, interacting with an H_2O molecule, might be attenuated, specifically if its frequency is close to the molecule's resonant one. Since backhaul links in cellular networks often operate around frequencies of 22 to 23 GHz, we focus on the 22.235 GHz absorbing line to monitor the water vapor.

The specific attenuation γ [dB/km] due to dry air and water vapor, at centimeter wavelengths, is well studied and can be evaluated (Rec. ITU-R P.676-6, 2005) using the following procedure:

$$\gamma = A_w + A_o \qquad [\mathrm{dB/km}] \tag{1}$$

$$\gamma = \frac{4\pi f \mathrm{N}''}{c}[\mathrm{m}^{-1}] = 0.1820 f \mathrm{N}'' \qquad [\mathrm{dB/km}] \tag{2}$$

Hence:

$$A_w = 0.1820 f \mathrm{N}'' - A_o \qquad [\mathrm{dB/km}] \tag{3}$$

Where:

A_w: The specific attenuation due to water vapor [dB/km].

A_o: The specific attenuation due to dry air [dB/km] (Assuming moist air A_o is negligible comparing to A_w since at frequencies of ~22 GHz, the attenuation is caused predominantly by the water vapor).

f: The link's frequency [GHz].

$\mathrm{N}''=\mathrm{N}''(\mathrm{p}, \mathrm{T}, \rho)$: The imaginary part of the complex refractivity measured in N units, a function of the pressure p[hPa], temperature T[C°] and the water vapor density ρ[g/m^3].

The detailed expression of the function N″ is described in the literature (Rec. ITU-R P.676-6, 2005).

Given measurements of the Received Signal Level (RSL), γ can be derived and then the induced attenuation A_w is assessed using Eq. (1).

Consequently, given the atmospheric temperature, pressure and the link's frequency, the water vapor density ρ[g/m^3] is estimated numerically, using the known relation between N$''$ and ρ.

As meteorological surface stations normally do not provide the absolute moisture ρ, it was derived using the following formulas (Rec. ITU-R P.676-6, 2005; Bolton, 1980):

$$e_s = 6.112 \exp\left(\frac{17.67T}{T + 243.5}\right) \tag{4}$$

$$e = \rho \frac{T + 273.15}{216.7} \tag{5}$$

$$\frac{e}{e_s} 100\% \equiv RH \tag{6}$$

e_s- The saturation water vapor pressure [hPa].
e- The water vapor partial pressure [hPa].
T- The temperature [°C].
ρ - The water vapor density ρ [g/m^3].

Hence:

$$\rho = 1324.45 \times RH \times \frac{\exp\left(\frac{17.67T}{T+243.5}\right)}{T + 273.15} \tag{7}$$

3 Statistical analysis

The correlation analysis was performed by the Pearson's correlation test, while the level of significance was set to 0.05.

The Root Mean Square Error (RMSE) in % was used according to the following definitions:

$$\mathrm{RMSE}\ [\mathrm{g/m^3}] = \sqrt{\frac{\sum_{i=1}^{N}(\rho_{mi} - \rho_{gi})^2}{N}} \tag{8}$$

$$\mathrm{RMSE}\ [\%] = \frac{\mathrm{RMSE}[\mathrm{g/m^3}]}{\sum_{i=1}^{N}\rho_{mi} \Big/ N} \times 100\% \tag{9}$$

ρ_{mi} - The water vapor density as measured using the microwave link [g/m^3].
ρ_{gi} - The water vapor density as measured using the humidity gauge [g/m^3].
N - The number of samples.

4 Results

Moisture observations using microwave links were made in several different locations in Israel, and at several different times. The results presented here (Figs. 1 and 2) are for Haifa (northern Israel; link frequency 22.725 GHz) and Ramla (central Israel; 21.325 GHz), during November 2005 and April–May 2007, respectively.

Figure 2 presents results for inter-daily variations in the absolute moisture which were calculated using data obtained from the wireless communication network, as compared to in-situ measurements, over a month. The results show very good match between the conventional technique and the novel method, the correlation coefficient between the time series in the two presented cases is 0.9 and 0.82, respectively. In both cases, the p value is less than 0.05. The RMSE were found to be 20.8% for the northern site and 33.1% for the central site measurements. Similar comparisons were performed for other links and other time slots showing correlations in the range of 0.5–0.9, depending largely on the representativity of the specific surface station. The system from which the data was collected captures a single signal every 24 h at 03:00 a.m. The surface station observations used were taken from the vicinity of the link's area at the same hour. Since rainfall causes additional signal-attenuation, days when showers occurred approximately at 03:00 a.m. till 04:00 a.m. (according to close by surface stations), were excluded.

The largest difference between the traditional and the novel measurement methods (Fig. 2b) appears on the night of 6 May 2007. This night was a holiday in Israel (Lag Ba'omer), where hundreds of bonfires were lit all across the country. As a result, many particles were released into the low atmosphere speeding up the creation of smog and possibly fog (the measured relative humidity by a radiosonde launched at 03:00 a.m. from Beit Dagan (Fig. 1b), a few km away from the microwave link, at an altitude of 95 m a.s.l. was 97%). The reason for the additional attenuation observed by the microwave link (expressed by a higher moisture level) might be due to local fog (Raghavan, 2003), implying that the system may provide the ability to monitor this phenomenon through the use of wireless communication data. When excluding the 6 May measurement, the correlation increases to 0.85 and the RMSE decreases to 30.2%. Further investigation is needed concerning this point.

5 Conclusions

Our results show good agreement with the current conventional way to measure water vapour over the low troposphere. However, since measurements from the microwave link are line integrated data, where in-situ measurements are point measurements in a humidity gauge, some disparities are caused. In addition, the difference in location between the measurement sites and particularly the difference in altitudes which can be significant at night hours, introduces additional disparities. The wireless measurement technique can thus either replace existing techniques or preferably be used in conjunction with them in order to obtain more accurate moisture fields. Given the newly available high resolution data provided by the wireless communication facilities, improved initialization of atmospheric models can be achieved, thus enhancing prediction and hazards warning skills as well as providing a better understanding of the global climate system.

Acknowledgements. We wish to acknowledge and thank Y. Dagan and Y. Eisenberg (Cellcom) for their cooperation and for providing the microwave data.

We also thank B. Goldman (Haifa District Municipal Association for the Environment) and A. Arie (Meteo-tech) for humidity gauge data.

This work was supported by a grant from the Yeshaya Horowitz Association, Jerusalem.

References

Allan, R. P., Shine, K. P., Slingo, A., and Pamment, J. A.: The dependence of clear-sky outgoing long-wave radiation on surface temperature and relative humidity, Q. J. Roy. Meteor. Soc., 125, 2103–2126, 1999.

Bolton, D.: The Computation of Equivalent Potential Temperature, Mon. Weather Rev., 108, 1046–1053, 1980.

Ducrocq, V., Ricard, D., Lafore, J. P., and Orain, F.: Storm-scale numerical rainfall prediction for five precipitating events over France: On the importance of the initial humidity field, Weather Forecast., 17, 1236–1256, 2002.

Leijnse, H., Uijlenhoet, R., and Stricker, J. N. M.: Rainfall measurement using radio links from cellular communication networks, Water Resour. Res., 43, W03201, doi:10.1029/2006WR005631, 2007.

Leijnse, H., Uijlenhoet, R. and Stricker, J. N. M.: Hydrometeorological application of a microwave link: 1. Evaporation, Water Resour. Res., 43, W04416, doi:10.1029/2006WR004988, 2007.

Lilly, D. K. and Gal-Chen, T.: North Atlantic Treaty Organization & Scientific Affairs Division. Mesoscale meteorology-theories, observations, and models, Reidel, Dordrecht, Netherlands, 1983.

Meeks, M. L.: Astrophysics, Academic Press, New York, 1976.

Messer, H., Zinevich, A., and Alpert, P.: Environmental monitoring by wireless communication networks, Science, 312, p. 713, 2006.

Messer, H.: Rainfall monitoring using cellular networks, IEEE Signal Proc. Mag., 24, 142–144, 2007.

Raghavan, S.: Radar Meteorology. Kluwer Academic Publishers, Dordrecht, 2003.

Rec. ITU-R P.676-6: Attenuation by atmospheric gases, ITU-R Recommendations, September, 2005.

Shay-El, Y. and Alpert, P.: A Diagnostic Study of Winter Diabatic Heating in the Mediterranean in Relation to Cyclones, Q. J. Roy. Meteor. Soc., 117, 715–747, 1991.

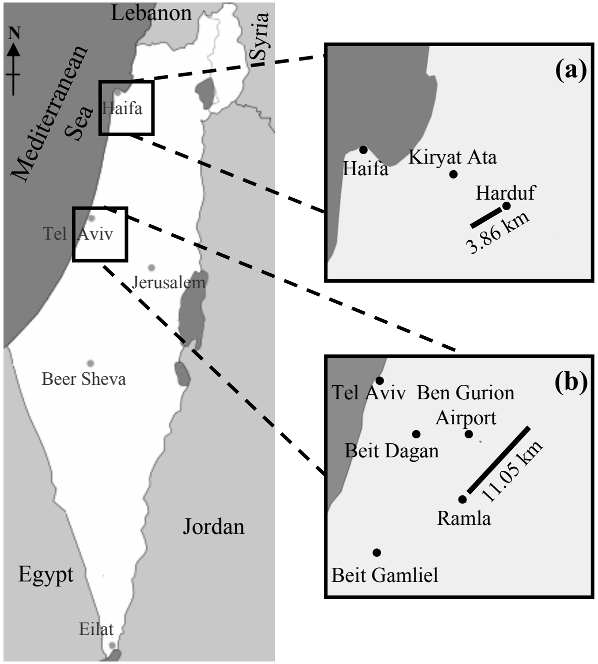

Fig. 1. The examined regions:
(a) The microwave link (3.86 km long, marked as a line) in front of Kiryat Ata (where the humidity gauge is located), Haifa bay. The distance from the surface station to a point located in the middle of the wireless link is 7.5 km. The surface station is situated 45 m a.s.l., while the microwave transmitter and receiver are located on two hills: 265 and 233 m a.s.l.
(b) The microwave link (11.05 km) in front of Ben-Gurion airport (humidity gauge's location), central Israel. The distance from the surface station to a point located in the middle of the link is 5 km. The airport surface station is situated at 41 m a.s.l., while the link's transmitter and receiver are located at heights of 116 and 98 m a.s.l.

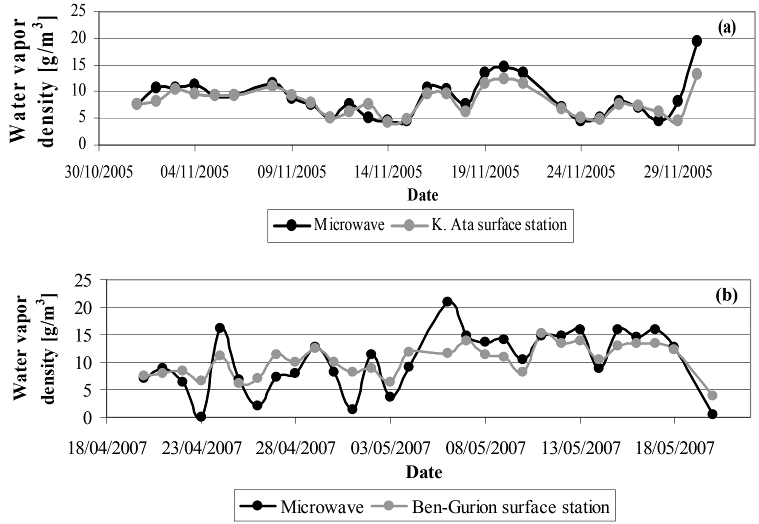

Fig. 2. The water vapor density ρ (g/m^3) as estimated using RSL measurements from the microwave link data (dark) vs. conventional humidity gauge data (bright).
(a) Northern Israel – The observations were made during the month of November 2005, where 2 rainy days were excluded (7 and 22 November). The link's frequency is 22.725 GHz. The calculated correlation between the two curves is 0.9 while the RMSE is 20.8%.
(b) Central Israel – The measurements were taken between 20 April and 20 May 2007, excluding 2 days when showers occurred (5 and 19 May). The link's frequency is 21.325 GHz and the calculated correlation between the time series is 0.82 with RMSE of 33.1%.

ACPD
8, 11673–11684, 2008

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion